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# Simultaneous estimates of cloud and rainfall parameters in the atmospheric vertical column above the Atmospheric Radiation Measurement Program southern Great Plains site

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[1] A novel remote sensing approach to simultaneously retrieve cloud liquid water paths (LWP) and ice water paths (IWP) and mean rainfall rate in a vertical atmospheric column was applied for stratiform-like precipitation events observed during the warm period of 2007 at the southern Great Plains site of the Atmospheric Radiation Measurement (ARM) Program. The retrieval method is based on multifrequency radar measurements at W, $K_a$, and S bands and raindrop size distribution estimates from a ground-based impact disdrometer. The radar measurements also provide a robust separation of the liquid, mixed, and ice hydrometeor layers. Characteristic values of LWP are about 300–400 g $m^{-2}$, although values up to 1000 g $m^{-2}$ and higher are not uncommon. There is on average insignificant correlation between cloud LWP and rainfall rates. IWP, which represents the precipitating cloud part of the atmospheric column that is observed above the freezing level, usually significantly exceeds cloud LWP in the liquid hydrometeor layer and can reach values of approximately $10^4$ g $m^{-2}$ and even higher. On average, mean rainfall in the liquid layer, $R_m$, increases with an increase in ice mass observed above the melting layer, although a corresponding mean correlation coefficient between $R_m$ and IWP is only 0.32. There is noticeable variability in IWP-$R_m$ relations between individual events. Storm dynamics is likely to influence the correlation between cloud and rainfall parameters as inferred from simultaneous columnar retrievals. Initial estimates indicate that IWP and rainfall are stronger related for events which exhibit lower vertical variability of wind.

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## 1. Introduction

[2] Clouds are one of the crucial components of the Earth's radiation budget. While studies of nonprecipitating clouds have a relatively long history, modeling and experimental studies of precipitating clouds and their radiative impact also have recently become an important research topic, drawing attention within the U.S. Department of Energy's Atmospheric Radiation Measurement (ARM) Program [*Ackerman and Stokes*, 2003]. Such studies are also one of the focal research points for the CloudSat community [*Stephens et al.*, 2002].

[3] Until recently precipitating cloud studies were hampered to a significant degree by the lack of joint simultaneous retrievals of cloud and rainfall parameters. Radar-based retrievals are usually developed either for precipitation (e.g., rainfall) or for nonprecipitating clouds. Centimeter wavelength radars (the wavelength, $\lambda \sim 3-10$ cm), which are traditionally used for rainfall studies, are typically not very sensitive to cloud particles. As in situ measurements show [e.g., *Mazin and Khrgian*, 1989], liquid cloud drops and raindrops can coexist in the same volume. In this case, cloud contributions to the total radar reflectivity are several orders of magnitude smaller than contributions from rain because backscatter cross sections are proportional to higher moments of particle size distributions (e.g., to the sixth moment in case of Rayleigh scattering).

[4] Millimeter wavelength radars ($\lambda \sim 3-10$ mm), which are often used for remote sensing of nonprecipitating clouds, suffer significant signal loss due to attenuation in rainfall. While presence of rain masks backscatter signals from clouds, the attenuation also presents a major obstacle for retrieving rainfall parameters with traditional radar methods that rely on measurements of absolute values of the equivalent radar reflectivity, $Z_e$.

[5] Absorption-based algorithms for passive multichannel microwave radiometers (MWRs) have a long history of retrieving liquid water path (LWP) in nonprecipitating clouds [e.g., *Solheim et al.*, 1998; *Turner*, 2007]. In rainy conditions, however, conventional MWR-based LWP estimates are generally not valid as a result of the violation of the Rayleigh assumption in the presence of larger raindrops and due to

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strong absorption by the melting hydrometeors which are usually a part of precipitating cloud systems. Partitioning total liquid between cloud and rainfall contributions using passive measurements is also problematic, although polarimetric MWR data at slant paths can potentially offer some hope (given that observed brightness temperatures are not saturated) [e.g., *Czekala et al.*, 2001].

[6] While backscatter from a liquid cloud and rainfall of comparable water contents differs greatly, attenuation usually does not. Knowing total attenuations at two different millimeter wavelength attenuating frequencies (e.g., at $\lambda \sim 3$ mm and $\lambda \sim 8$ mm) in a hydrometeor layer containing clouds and rain provides the possibility of estimating mean (or integrated) rainfall and cloud parameters of this layer. An attenuation-based remote sensing method to estimate mean rainfall rate and cloud liquid water path (LWP) in a stratiform precipitation layer located between surface and the melting layer using ARM radars was recently suggested by *Matrosov* [2009]. With the use of a reflectivity constraint provided by a weather radar operated on nonattenuated S band frequency ($\lambda \sim 10$ cm), this method also allows estimates of the ice water path (IWP) of the cloud part of precipitating system observed above the melting (freezing) level.

[7] This study presents results of applying the aforementioned method to estimate IWP, LWP, and mean rainfall rate for stratiform precipitation events observed at the southern Great Plains (SGP) ARM Climate Research Facility (ACRF) during the warm period of 2007 when all required radar data streams were available. The retrieval results are analyzed statistically for the purpose of assessing possible interrelations between cloud and rainfall components of the water cycle.

## 2. A Brief Description of the Remote Sensing Approach

[8] The retrieval approach is discussed in detail by *Matrosov* [2009], so only a brief description is given here. The vertically pointing $K_a$ band millimeter wavelength Cloud Radar (MMCR) and W band ARM Cloud Radar (WACR), which operate at wavelengths of 8.7 and 3.2 mm, respectively [*Kollias et al.*, 2007], are the two main instruments used for retrievals. The cloud LWP and mean rainfall rates for stratiform precipitation events are retrieved on the basis of vertical changes in radar reflectivities observed in the whole liquid hydrometeor layer from the lowest range gate, which is free from saturation effects, to the lower boundary of the melting layer. It becomes possible because attenuation at these wavelengths is strong, and the wavelength spectral dependence of the attenuation is different for a small cloud drop fraction (less than about 50–100 $\mu$m) and for larger raindrops.

[9] The underlying assumption is that the total vertical reflectivity change in a stratiform rainfall at the ARM radar frequencies is dominated by hydrometeor attenuation, and the vertical changes of nonattenuated reflectivities are small compared to attenuation effects. Gaseous attenuation due to water vapor and oxygen is accounted for using model calculations. The copolar WACR mode and the MMCR precipitation mode measurements are used in the general version of the remote sensing method for retrievals of cloud LWP and mean rainfall rate. The MMCR precipitation measurement mode was specifically designed to avoid receiver saturation issues and uncertainties due to lower Nyquist velocities used in other MMCR modes. It was recently revealed (P. Kollias and S. Giangrande, private communication, 2008), however, that this mode often has some artifacts, which prevent its effective use. In the simplified version of the method described by *Matrosov* [2009] and employed here, disdrometer-based rainfall rates are used as a proxy for the mean rainfall rates in a liquid hydrometeor layer and the W band attenuation due to rain is estimated. These estimates are then compared to the observed values and the attenuation excess (after correcting for gaseous attenuation) is attributed to the liquid cloud attenuation for assessing corresponding LWP values.

[10] Justifications for the use of the simplified version of the retrieval scheme include a generally low variability of nonattenuated reflectivity (and hence rainfall rate) with height in stratiform rain [*Bellon et al.*, 2005; *Matrosov et al.*, 2007] and a higher cloud-to-rainfall attenuation ratio at W band (compared to $K_a$ band). In stratiform rains, this variability is usually very modest and amounts to about 1–1.5 dB (in terms of standard deviation) at precipitating radar frequencies [e.g., *Matrosov et al.*, 2007]. The vertical changes of W band nonattenuated reflectivity (which is accounted for as an error source when estimating retrieval uncertainties) is further subdued by the strong non-Rayleigh scattering effects which result in only very weak variability of nonattenuated reflectivity with rainfall rate. The retrieval uncertainties for this simplified retrieval method version are similar to those for the full version of the technique [*Matrosov*, 2009].

[11] The upper boundary of the liquid hydrometeor layer and the height of the melting level (i.e., the height of the 0° isotherm) are estimated from cross-polar WACR measurements, which exhibit a strong depolarization maximum due to scattering from melting hydrometeor, and from the MMCR and WACR vertical Doppler velocity measurements, $V_D$, which show a distinct transition from small values that are characteristic for snow to the values that are typically observed in rain ($V_D > 5$ m s$^{-1}$). Interpolated radiosonde sounding data were used for temperature estimates in the hydrometeor layer. Note that due to the differential character of attenuation-based retrievals, LWP and mean rainfall estimates are not affected by uncertainties in the absolute calibration of the radars.

[12] While LWP and mean rainfall rate retrievals are based on attenuation, which is strong in liquid phase, the ice phase retrievals at heights above the freezing level are performed using the absolute radar measurements from the MMCR general mode, which is more sensitive ($\sim$−33 dBZ at 10 km) than the precipitation mode. The attenuation of radar signals in dry ice and snow is small and can be neglected for most practical cases of stratiform precipitation, although ground-based MMCR general mode measurements need to be corrected for the total attenuation in the liquid and melting layers and also by attenuation due to a wet radome. Although liquid phase hydrometeor attenuation can be accounted for theoretically on the basis of the retrieval results in the liquid layer, the wet radome attenuation is generally not known and estimates of attenuation in the melting layer have high uncertainties [*Matrosov*, 2008]. To overcome this issue, the measurements from Weather Service Radar-1988 Doppler

(WSR-88D) operated at S band and located at the Vance Air Force Base (∼60 km from the SGP Central Facility) are used to correct MMCR measurements above the freezing level. Non-Rayleigh scattering effects are accounted for during the correction procedure.

[13] The WSR-88D data above the SGP site typically can be obtained every 6 min from volume scans performed by the Vance radar, although only a few data points in a reconstructed S band vertical profile are usually available in the ice parts of a precipitating system. These points are used for correction of MMCR data, and, as a result, a high spatial resolution (∼90 m) MMCR corrected reflectivity profile becomes available over the SGP Central Facility. Ice water content (IWC) values are then calculated for each profile using a $K_a$ band IWC-$Z_e$ relation [*Matrosov*, 2009] obtained with the data set from *Matrosov and Heymsfield* [2008]. IWP estimates are obtained by vertically integrating IWC values over heights above the melting level.

[14] An impact-type ground-based Joss-Waldvogel disdrometer (JWD) [*Joss and Waldvogel*, 1967] recently deployed at the SGP site is used to derive raindrop size distributions (DSDs) for rain parameter constraint at the surface and for case-tuning relations between rainfall rate and attenuation at W band. Note that $K_a$ band rain attenuation and $K_a$ and W band liquid water cloud attenuations do not exhibit significant variability due to DSD details [e.g., *Matrosov*, 2005; *Matrosov et al.*, 2006]. The JWD DSD estimates are corrected for dead-time effects [*Sheppard and Joe*, 1994], which brings the disdrometer estimates of total rainfall accumulation to a close agreement with measurements from the standard rain gauge deployed near the JWD. JWD DSDs are also used to verify the absolute calibration of the Vance WSR-88D data [*Matrosov*, 2009].

[15] As a result of the application of the described remote sensing approach, the time series of IWP (for the cloud regions above the melting level), cloud LWP, and mean rainfall rate (for the liquid layer below the melting layer) averaged in 6 min intervals are obtained for the vertical atmospheric column above the SGP site Central Facility. This approach cannot retrieve supercooled liquid amounts which could be present above the melting level. The 6-min time resolution is chosen, in part, to match the availability of the nonattenuated S band measurements above the site and also to reduce statistical variability of measured and retrieved parameters.

[16] The retrieval accuracy for typical stratiform rainfall conditions ($R \sim 2$–$3$ mm h$^{-1}$) is approximately 30–35% for mean rainfall rates, and about 200–300 g m$^{-2}$ for cloud LWP. Retrieval uncertainties for IWP estimates can be as high as a factor of 2, which is, however, not unusual for the radar reflectivity based estimators of IWP as comparisons of different ice cloud retrieval techniques indicate [*Comstock et al.*, 2007].

## 3. Retrieval Results Over the ARM SGP Site

### 3.1. Selection of Retrievals Events

[17] The approach used in this study is applicable to stratiform precipitation events for which hydrometeor phases such as liquid (containing rain and liquid water clouds), mixed (i.e., hydrometeors observed in the melting layer) and solid (ice and snow regions above the melting level) are easily separated using polarimetric and Doppler radar measurements from ground-based ARM radars. Stratiform events (as compared to convective rains) are characterized by a longer duration and lighter rainfall, which exhibit low-to-moderate variability in rain rates. All precipitation events observed during the April–October 2007 period at the SGP ACRF site were examined with regards to the possibility of applying the remote sensing method to simultaneously estimate cloud and rainfall parameters in the vertical atmospheric column.

[18] Additional selection criteria included thresholding on the lowest and highest rainfall rates. Time intervals with JWD rainfall rates less than 0.5 mm h$^{-1}$ were excluded because, at such low rainfall rates, total attenuations are relatively small, which might lead to higher retrieval uncertainties [*Matrosov*, 2009]. Excluded also were periods with rainfall rates greater than 15 mm h$^{-1}$, because higher rainfall rates are typically associated with stronger convective activity which may result in significant vertical inhomogeneity of rain. Another reason for this exclusion is that (as comparisons of MMCR and the Vance radar show) the total two-way attenuation for such rains is typically higher than 30–35 dB, so the MMCR general mode would not "see" upper cloud parts with reflectivities less than about 0 dBZ. In typical stratiform precipitating systems ice parts with $Z_e < 0$ dBZ usually contribute less than 10% of the total IWP [*Matrosov and Heymsfield*, 2008] and the resulting possible underestimation of IWP due to missing cloud parts near the upper cloud boundaries is small. For precipitating systems with $R > 15$ mm h$^{-1}$ and thicker liquid layers, however, ground-based IWP retrievals could result in some significant negative biases.

[19] On the basis of the criteria formulated above, 11 observed events at the ARM SGP site during the warm period of 2007 could be used for full retrievals. All these events were observed in May and June 2007, which was one of the wettest May–June periods on record in this area. Some of the retrieved events represented postconvective trailing stratiform rains that lasted 2–4 h. Others (e.g., the 1 May 2007 event described in more detail by *Matrosov* [2009]) were long multihour stratiform rains. As radar Doppler and polarimetric data showed, the melting layer for all these events was typically about 500 m thick, and it usually was confined between heights of 2.7 and 3.5 km above ground level, thus an average thickness of the liquid hydrometer layer was about 3 km. A number of precipitation events during the warm period outside May and June were not usable for retrievals because one or several crucial observational data sets needed for retrievals were not available for those events. For example, no JWD data were available in April 2007. The lack of the qualified events during July–October 2007 is explained because the WACR was not operational for most of this period.

### 3.2. An Illustration of Retrievals

[20] A rainfall event observed between about 0930 and 1320 UTC on 24 May 2007 was characteristic of the SGP precipitating systems in May–June 2007. This event was also typical in a sense that as it will be seen later in table 1 and Figure 5, the cloud and precipitation parameters and their interrelations were close to the average results. The time-height cross sections of the MMCR general mode and WACR copolar mode data for this observational case are shown in Figure 1.

**Table 1.** Parameters in the Experimental IWP = $aR_m^b$ and LWP = $cR_m^d$ Relations for the SGP Precipitating Events and the Corresponding Power Law Correlation Coefficients[a]

| Date of Event | Event Number | Duration | $a$ | $b$ | $r_{IWP\text{-}R}$ | $n$ | $c$ | $d$ | $r_{LWP\text{-}R}$ |
|---|---|---|---|---|---|---|---|---|---|
| 1 May 2007 | 1 | 12 h | 1120 | 0.69 | 0.36 | 111 | 480 | −0.01 | 0.02 |
| 7 May 2007 | 2 | 8.2 h | 5400 | 0.02 | 0.01 | 77 | 430 | −0.09 | 0.08 |
| 8 May 2007 | 3 | 4.6 h | 1840 | 0.28 | 0.37 | 47 | 290 | 0.41 | 0.40 |
| 9 May 2007 | 4 | 2.3 h | 3600 | −0.31 | 0.43 | 24 | 210 | −0.46 | 0.35 |
| 24 May 2007 | 5 | 3.9 h | 3700 | 0.32 | 0.42 | 37 | 395 | −0.02 | 0.03 |
| 27 May 2007 | 6 | 5.3 h | 1120 | −0.02 | 0.03 | 44 | 400 | −0.16 | 0.18 |
| 30 May 2007 | 7 | 2.3 h | 6800 | −0.08 | 0.19 | 23 | 360 | −0.27 | 0.21 |
| 13 June 2007 | 8 | 2.0 h | 720 | 0.46 | 0.34 | 16 | 920 | −0.71 | 0.19 |
| 14 June 2007 | 9 | 7.4 h | 1390 | 0.75 | 0.44 | 48 | 390 | 0.38 | 0.29 |
| 15 June 2007 | 10 | 3.0 h | 1910 | 0.60 | 0.38 | 29 | 260 | −0.19 | 0.13 |
| 20 June 2007 | 11 | 3.8 h | 5900 | 0.11 | 0.34 | 37 | 310 | −0.13 | 0.15 |

[a]The number of retrieval points ($n$) for each event is also shown.

[21] As seen from Figure 1, the separation between the ice and liquid phases in a precipitating system is rather distinct. The melting layer is seen as the bright band in MMCR reflectivity data, and the vertical Doppler velocity measurements nicely indicate the rain layer upper boundary at a height of about 3 km. Note that there is Doppler velocity measurement aliasing in general mode rain measurements due to the lower Nyqust velocity (~3.4 m s$^{-1}$) in this mode The $V_D$ values in Figure 1b, however, were corrected for the aliasing effect. Radar reflectivity measurements in the liquid hydrometeor layer (Figures 1a and 1c) exhibit distinct attenuation patterns of $Z_e$ diminishing with altitude. These patterns are aligned approximately vertically which is characteristic of stratiform rain that does not vary significantly with height [*Matrosov*, 2005].

[22] For the first half an hour of the event, the rainfall rates, as inferred from the JWD data were greater than 15 mm h$^{-1}$, peaking at about 30 mm h$^{-1}$ around 0945 UTC. Such heavy rain resulted in the total attenuation of WACR measurements in the upper part of the liquid hydrometeor layer. MMCR measurements also suffered significant attenuation and, at peak rainfall rates, they were completely attenuated above 4.5 km. After the heavy convective rain departed the SGP Central Facility after around 1000 UTC, stratiform-like rainfall was observed for the remainder of the event. As evident from Figure 1a, this rainfall attenuated the MMCR reflectivity measurements in the ice part of the precipitating system, although this attenuation was not very severe and detectable cloud top heights during rain at the ground were only slightly lower compared to rain-free periods before 0930 and after 1400 UTC. The shorter wavelength WACR measurements, however, suffer significantly stronger attenuation (Figure 1c), which indicates limitations for the use of ground-based W band radar measurements of ice parts of precipitating systems.

[23] The time series of the estimated cloud LWP, IWP and mean layer rainfall rate, $R_m$, for the stratiform-like part of the SGP event of 24 May 2007 are shown in Figure 2. It can be seen that IWP values are quite high and, sometimes, they exceed cloud LWP values in the same vertical atmospheric column by an order of magnitude. This may reflect the predominant mechanism of forming liquid precipitation (for the stratiform part of this event) which is melting of ice/snow particles that have formed and grown during their descent through the ice cloud part of the precipitating system toward the melting level. Maximum cloud LWP values retrieved for this precipitating event reached about 1000 g

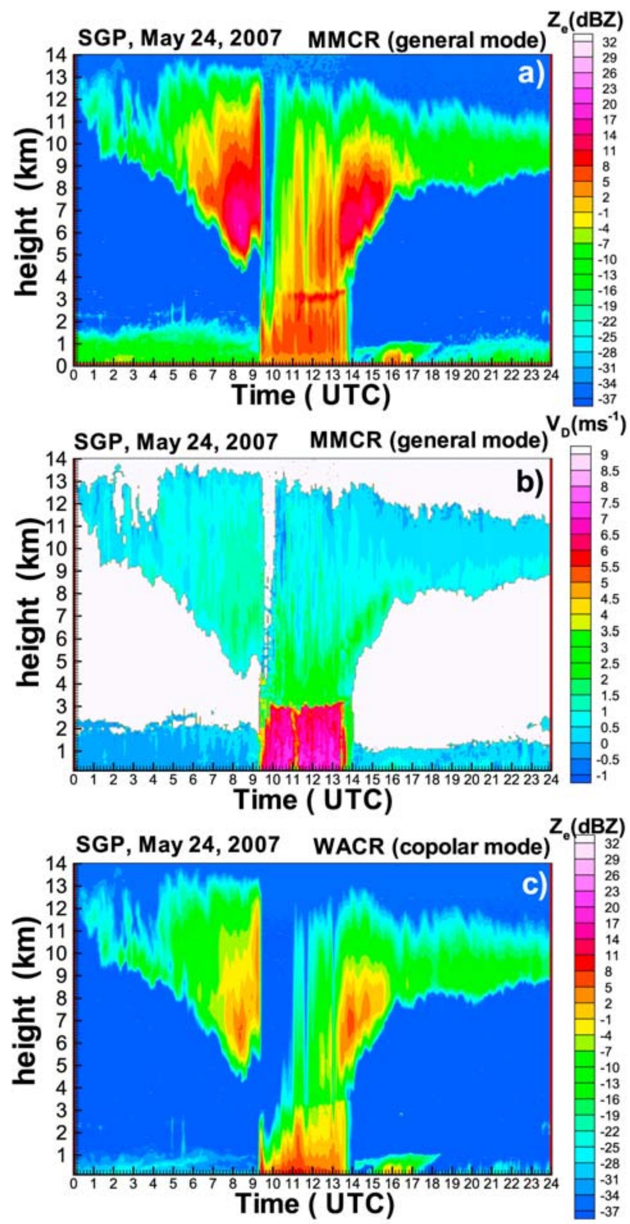


**Figure 1.** Time-height cross sections of the MMCR general mode (a) reflectivity and (b) vertical Doppler velocity and (c) WACR copolar mode reflectivity observed on 24 May 2007 at the SGP ACRF.

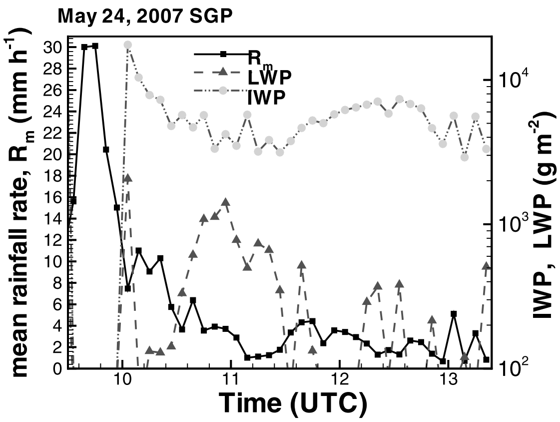


**Figure 2.** Time series of the retrieved mean rainfall rate, $R_m$, and cloud LWP and IWP for the event of 24 May 2007. IWP and LWP retrievals are not available during the convective period prior 1000 UTC.

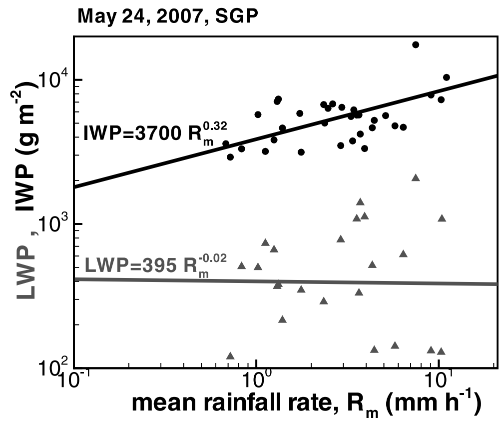


**Figure 3.** Scatterplots of the retrieved mean rainfall rate, $R_m$, and IWP (circles) and $R_m$ and cloud LWP (triangles) for the event observed on 24 May 2007.

m$^{-2}$, although typical values were around 300–400 g$^{-2}$. There is more variability for lower LWP estimates, which can be explained, in part, by retrieval uncertainties.

## 4. Relations Between Cloud and Rainfall Parameters

[24] The remote sensing retrievals results described in section 3 can be used for assessing possible statistical relations between vertically integrated cloud properties and mean rainfall. For a precipitation event of 24 May 2007, Figure 3 shows scatterplots between $R_m$ and IWP and cloud LWP. Relations between rain and cloud parameters are sought in a power law form, which often is used in atmospheric physics to describe the correspondence between different quantities and in various parameterization schemes:

$$\mathrm{IWP} = aR_m^b \tag{1}$$

$$\mathrm{LWP} = cR_m^d. \tag{2}$$

[25] It can be seen from Figure 3 that there is some noticeable relation between IWP and $R_m$ generally indicating more significant rainfall from precipitating cloud systems with larger values of the total ice mass. The power law correlation coefficient between IWP and $R_m$ is, however, only about 0.4. Retrieval results for 24 May 2007 show no significant relation between cloud LWP and mean rainfall (the correlation coefficient between LWP and $R_m$ is 0.03) with a mean value of the liquid water path around 400 g m$^{-2}$. This is, possibly, evidence that melting processes rather than warm rain processes are the primary mechanism for formation of stratiform rain. There is also no significant relation between LWP and IWP ($r < 0.1$) in the observed system (not shown).

[26] Figure 4 shows the best power law fits (1) and (2) for all the 2007 SGP precipitation events that passed the selection criteria formulated in section 3.1 and for which a full set of observational data (i.e., MMCR, WACR, WSR-88D, and JWD data) was available. The power law fits cover the range of $R_{\mathrm{m}}$ which was considered appropriate for applying the retrieval approach discussed in section 2. The best fit coefficients $a$, $b$, $c$, and $d$ and the corresponding power law correlation coefficients are given in Table 1.

[27] It can be seen from Figure 4a that the IWP-$R_m$ power law best fit approximations generally cover the IWP range between about 400 and 10,000 g m$^{-2}$ (although individual data points obviously can be outside this range of IWP). This

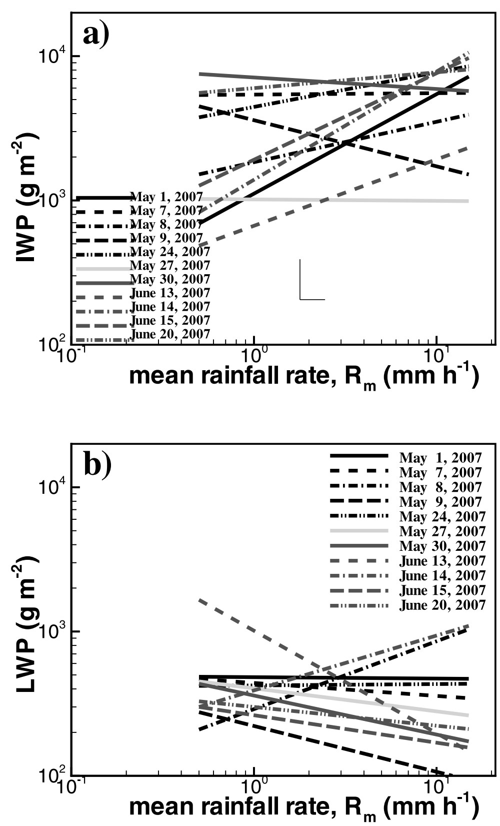


**Figure 4.** Best fit power law (a) IWP-$R_m$ and (b) LWP-$R_m$ approximations for the precipitation events observed at the SGP ACRF during May–June 2007. The thin lines in the lower part of Figure 4a represent a factor of 2 (for IWP) and 35% (for $R_m$) error bars.

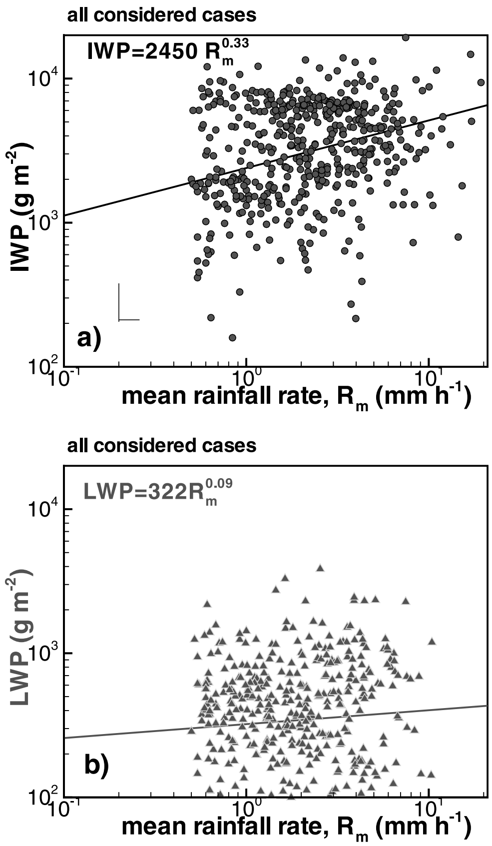


**Figure 5.** Combined (a) IWP-$R_m$ and (b) LWP-$R_m$ scatterplots for all considered cases.

IWP range can, probably, be considered as a typical one for the total ice content in established stratiform precipitation events (at least for the May–June 2007 period) observed around the SGP area. It is interesting to note that while greater IWP values usually correspond to heavier rainfalls (i.e., the exponent $b$ in (1) is usually positive), there are a few observational events (e.g., 7, 27, and 30 May 2007) when there is no significant correlation between IWP and $R_m$ and corresponding relations are practically flat. The 9 May 2007 event stands out from other cases by exhibiting a noticeable negative correlation between these parameters.

[28] If all processed observational events are considered in combined scatterplots (Figure 5a), the average total ice content–rainfall relation is IWP $\approx 2450\, R_m^{0.33}$ (where IWP is in g m$^{-2}$ and $R_m$ is in mm h$^{-1}$). According to this average relation, typical changes of IWP over the considered interval of rain rates are greater than a factor of 3 which is greater than expected uncertainty of IWP retrievals, which rather conservatively are estimated as about a factor of 2 [*Matrosov*, 2009]. Note also that a part of the IWP estimate uncertainty comes from errors in the absolute radar reflectivity calibration and correction. This part of the error does not affect the trend of the IWP -$R_m$ relation but rather shifts this relation along the vertical axis.

[29] The corresponding power law correlation coefficient between columnar values of IWP and $R_m$ is, however, not very large ($r_{IWP\text{-}R} \approx 0.32$), which reflects only a moderate correlation between these two parameters of the precipitating cloud systems as inferred from the measurements in the same vertical column. As seen from Table 1 for individual events, this coefficient varies from about 0 (i.e., no correlation) to values up to 0.44 indicating some noticeable correlation.

[30] It is instructive to look in some more detail into the 9 May 2007 event because of its relative uniqueness. Figure 6 shows the time height cross sections of the MMCR, WACR, and Vance radar (a National Weather Service identifier for this radar is KVNX) data for this 3.5 h event. During the first 1.5 h, the ice part of the precipitating system above the melting level (which was observed at an about 3.4 km height) was rather thick and corresponding nonattenuated reflectivities (Figure 6c) were high. It resulted in larger IWP values. In the second half of the event, the ice cloud part became progressively thinner (as seen from all radar measurements

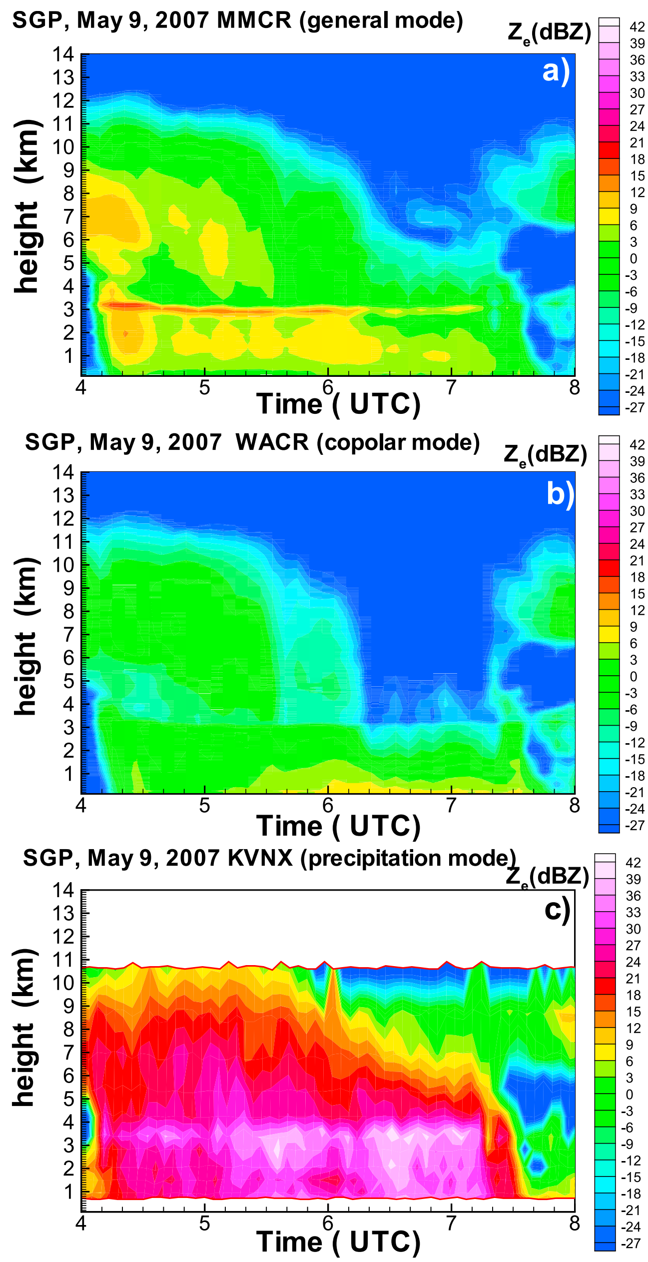


**Figure 6.** Time-height cross sections of the (a) MMCR general mode reflectivity, (b) WACR copolar mode reflectivity, and (c) KVNX S band reflectivity measurements observed on 9 May 2007 at the SGP ACRF.

including the KVNX radar), so IWP was decreasing after about 0530 UTC. At the same time, rainfall was generally heavier during this second period. It is evident from all instruments including the disdrometer (not shown) and radars. The S band reflectivities in the rain layer (Figure 6c) are higher than those in the first part of the event, and there is more attenuation of WACR and MMCR measurements because of rainfall. The dissipating ice part of the precipitating system observed simultaneously with more significant rainfall resulted in noticeable negative correlation between IWP and $R_m$. While this event was not characteristic of the whole data set and can be considered as an "outlier," observations show that situations with negative correlation between columnar IWP and $R_m$ values could happen. Without detailed 3-D wind measurements and modeling efforts, which are outside the scope of this observational study, it is difficult to speculate on the exact reasons of the increase in rainfall when IWP in the same vertical atmospheric column exhibits a decrease.

[31] Retrieved values of cloud LWP for all considered events are usually smaller than those for IWP in the same vertical column. Typically these values are approximately 300 – 400 g m$^{-2}$ and they do not exhibit much correlation with $R_{\mathrm{m}}$ (Figure 4b, Table 1). An average relation between the cloud and rainfall liquid components (Figure 5b) is rather flat: LWP = 322 $R_m^{0.09}$, with a correlation coefficient of only $r_{LWP\text{-}R} \approx 0.1$. Note that points with LWP < 100 g m$^{-2}$ were not included in Figure 5b because retrievals of such low-LWP values are generally unreliable [*Matrosov*, 2009]. The average LWP-$R_m$ relation is not very different from the one shown in Figure 3. The relative closeness of the average LWP-$R_m$ and, in some way, IWP-$R_m$ relations to the ones for the 24 May 2007 event supports a previous notion that this event was a representative precipitating cloud system case observed in May–June 2007 at the SGP ACRF.

[32] Since the considered remote sensing approach uses measurements of the total attenuation of radar signals in the liquid layer to estimate LWP, no retrievals of liquid water content (LWC) profiles are currently possible (unlike for retrievals of IWC profiles which are estimated from the vertical profiles of absolute reflectivities that were corrected for the total attenuation). It is informative, however, to make some estimates of characteristic LWC values under some assumptions about the thickness of the liquid cloud layers which coexist with rainfall in a layer between the base of the melting layer and the ground.

[33] Experimental data provided by *Mazin and Khrgian* [1989] indicate that the liquid water parts of warm season midlatitude nimbostratus (NS) clouds, which are associated with stratiform rainfall, could be as thick as 2 km. These authors also show that LWC in NS clouds does not exhibit strong vertical dependence (unlike for adiabatic LWC in non-precipitating clouds). The typical values of LWP in the liquid hydrometeor layer (from retrievals described in section 3) of about 300–400 g$^{-2}$ and an assumption of the total cloud layer thickness of 2 km, one can get for a mean LWC an estimate of approximately 0.15–0.2 g m$^{-3}$ (or 0.3–0.4 g m$^{-3}$ for an assumption of 1 km total NS layer thickness). These values are generally consistent with the mean experimental values of LWC in midlatitude warm NS clouds (i.e., 0.25–0.35 g m$^{-3}$, as reported by *Mazin and Khrgian* [1989]). More robust estimates of LWC could be performed if the NS layer thickness were available at the ARM sites. However, there are no such measurements (ARM ceilometers and lidars can provide only estimates of cloud base heights, and the quality of these estimates in rainy conditions is not clear).

[34] It should be mentioned that the relatively high uncertainties of the retrieved ice and liquid cloud and rainfall parameters (as provided in section 2) could "mask" correlations among these parameters. It is believed, however, that the larger amounts of retrievals, as they become available, will substantiate estimates of the relations between these parameters, because partial balancing out of errors inherent to individual points will occur and the general trends in IWP-$R_m$ and LWP-$R_m$ relations could become more pronounced as larger data sets are used.

## 5. Analysis of the Observed Relations Between IWP and Rainfall

[35] While the observational correlation $r_{LWP\text{-}R}$ between the rainfall rate and cloud LWP for the majority of the considered events is insignificant, it is not so for $r_{IWP\text{-}R}$. Melting of ice and snow particles as they reach a 0°C isotherm is considered to be one of the main mechanisms of rainfall formation in the events which clearly exhibit radar bright band features; thus, some correlation between IWP and mean rainfall rate $R_m$ could be expected. Although the majority of the observed events indicate a noticeable correlation ($r_{IWP\text{-}R} > 0.3$), for few events, as seen from Table 1, this correlation is insignificant (it is customary in many statistical applications to consider correlation insignificant/low if the absolute value of the correlation coefficient is less than about 0.25–0.3). One of the reasons for decorrelation between IWP and $R_m$ could be a strong vertical dependence of horizontal advection, when significant wind shear exists between ice and rainfall parts of precipitating systems.

[36] Figure 7 shows scatterplots between $r_{IWP\text{-}R}$ and event mean wind speed ($\Delta V$) and direction ($\Delta\alpha$) differences between the rain and ice layers, which were calculated using the interpolated radiosonde soundings data. The change in the direction of horizontal wind is typically between 50° and 90° (Figure 7b), but there is no significant relation between $r_{IWP\text{-}R}$ and ($\Delta\alpha$). The lower correlation coefficients $r_{IWP\text{-}R}$, however, generally correspond to large values of wind speed differences ($\Delta V$ > 6 m s$^{-1}$, or so). While being mostly qualitative, these results suggest that wind sheer might play a role in decorrelating (i.e., reducing the corresponding correlation coefficient) mean rainfall rate and IWP values which are retrieved simultaneously in a vertical column.

[37] The derived power law IWP-$R_m$ relations for different observational cases exhibit noticeable variability in the slope magnitude (i.e., exponent $b$), which determines the range of IWP changes for a given range of variability in rain rate. While no significant influence of large-scale storm properties (e.g., storm duration) on this slope (and a value of $r_{IWP\text{-}R}$) was found for the available data set (corresponding scatterplots are not shown), there is some dependence of the exponent $b$ on the mean value of IWP. Figure 8 shows a scatterplot of $b$ versus mean IWP for the observational events which exhibited meaningful correlation ($r_{IWP\text{-}R} > 0.3$). It can be seen from Figure 8 that larger values of $b$ are generally associated with lower values of mean IWP, although the "outlier" case of 9 May 2007 does not follow a general trend. One possible

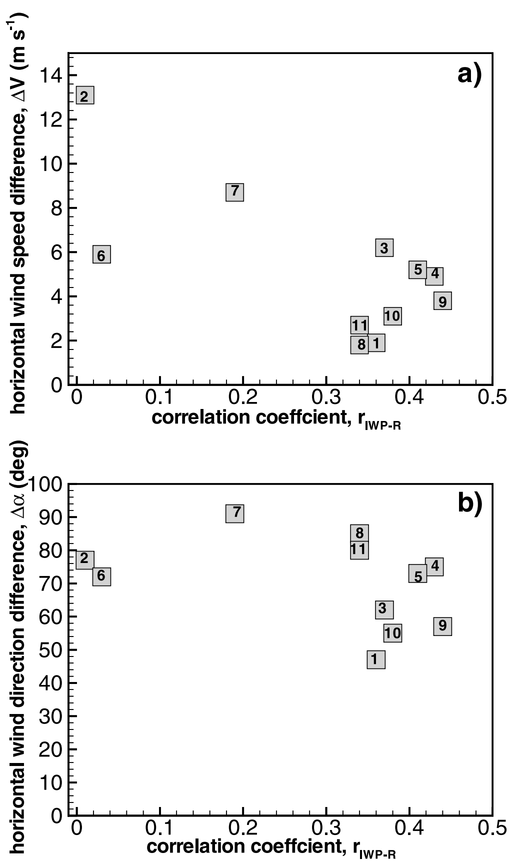


**Figure 7.** Correlation coefficient $r_{IWP\text{-}R}$ versus the mean (a) wind speed $\Delta V$ and (b) wind direction $\Delta\alpha$ differences between rainfall and ice cloud part layers. Event numbers (as in Table 1) are also shown.

explanation of this trend is that for events with larger mean IWPs, the observed dynamic range of IWP changes (for a given variability range in rain rates) is usually smaller because largest observed IWPs are capped by values of about $10^4 - 2 \times 10^4$ g m$^{-2}$ (at least in this observational data set, see Figure 4a).

[38] Given a small number of observational cases and limited capabilities in observing high resolution dynamical parameters, the presented analysis of IWP and $R_m$ relations and the corresponding correlations could be considered as qualitative one. High time and space resolution 3-D microphysical and wind mapping with an array of scanning radars, which is planned for the SGP ARM site, in the future might provide a more definite quantitative answer on how cloud and precipitation dynamics and microphysics influence the relations between ice cloud and rain columnar parameters. Microphysical modeling with accounting for cloud and precipitation dynamics may also provide more insights. Such modeling, however, is beyond the scope of this study.

## 6. Conclusions

[39] A multifrequency radar remote sensing approach that uses measurements from ground-based $K_a$, W, and S band radars and also impact disdrometer estimates of raindrop size distributions was applied to retrieve cloud and rainfall parameters in a vertical atmospheric column above the ARM SGP Central Facility in northern Oklahoma. This approach is applicable to persistent stratiform-type precipitation events for which liquid, mixed, and solid phase regions can be separated along a vertical coordinate using polarimetric and Doppler radar measurements. The retrievals were performed for the qualified precipitation events observed during the warm season of 2007 when all the required instruments were operational at the ARM SGP site.

[40] The simultaneously estimated hydrometeor parameters, which included IWP of cloud regions above the melting level and cloud LWP and the mean rainfall rate in a liquid hydrometeor layer, were analyzed. Mean estimates of cloud LWP were about 300–400 g m$^{-2}$, and they showed almost no significant correlation (except for a couple of observational events) with the intensity of rainfall resulting from the observed stratiform-like precipitating cloud systems. While 300–400 g m$^{-2}$ values were quite typical, it was not unusual for LWP to reach and even exceed 1000 g m$^{-2}$. The LWP retrievals are based on the estimates of radar signal attenuation in the whole liquid hydrometeor layer, so the vertical profiles of LWC are not available.

[41] IWP retrievals are based on IWC estimates derived from absolute millimeter wavelength radar reflectivity measurements corrected for the total attenuation caused by the liquid and mixed phase hydrometeors and wet radome using data available from a nearby WSR-88D radar which operates at an S band frequency. For stratiform-like precipitating events at SGP, derived IWP values were noticeably greater than cloud LWP, and they generally varied more than 1 order of magnitude from several hundreds of g m$^{-2}$ to slightly more than 10,000 g m$^{-2}$. Unlike for the liquid cloud component, there was, on average, a positive correlation between IWP and the resultant rain, for the majority of the considered events. The mean correlation coefficient, however, was only about 0.32, which is indicative of only moderate correlation between IWP and rainfall rate in the same vertical atmospheric column.

[42] It should be mentioned, however, that correlation between rainfall and IWP, as inferred from observations in a vertical column, might not be directly representative of the correlation between these parameters on larger scales because the vertical dependence of the horizontal advection and storm 3-D dynamics could decorrelate IWP above the melting layer and rainfall simultaneously observed below this

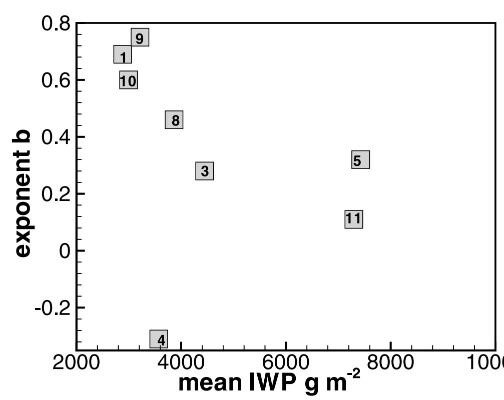


**Figure 8.** A scatterplot of the exponent $b$ (in IWP = $aR_m^b$) versus the mean IWP for the observed events. Event numbers (as in Table 1) are also shown.

layer. Relatively high retrieval uncertainties could also decorrelate retrieved parameters, especially for smaller data sets. While this study presents some initial insights into the correspondence between ice and liquid cloud and rainfall parameters in precipitating systems, larger data sets, better observations of cloud and rainfall dynamics are needed for more reliable estimations of relations between ice and liquid cloud and rainfall parameters. These larger data sets are likely to be available sometime in future when the W and $K_a$ band radars will be again collocated at the ARM SGP site. Better understanding of the influence of storm dynamics on the correspondence between ice and rainfall components of precipitating systems (as inferred from vertical column retrievals) could be gained for these future data sets since deploying an array of scanning radars for 3-D monitoring (including wind mapping) is also planned as an enhancement of observational capabilities at the ARM SGP facility. Estimates of optical thickness of cloud ice parts can also be performed in the future using relations between the extinction coefficient and radar reflectivity [e.g., *Matrosov et al.*, 2003].

[43] The presented analysis of relations between rainfall and cloud components of SGP precipitation systems corresponds to established stratiform-like events, which exhibited clear radar bright band features and were time persistent ($\sim$2–11 h) and had rainfall rates in a range of 0.5–15 mm $h^{-1}$. Lower rainfall rates usually do not provide large enough attenuations for retrievals, and heavier rains have higher vertical and temporal variability and can produce too much attenuation which might noticeably bias ice phase cloud estimates. The cloud top heights for the considered events were typically higher than 10 km AGL, and the freezing levels were observed at altitudes of about 4 km AGL.

[44] The main objective of this study was to present novel simultaneous retrievals (with corresponding uncertainties) of cloud and precipitation parameters for available experimental events thus addressing one of the ARM observational priorities which is a comprehensive representation of hydrometeors in a vertical column. While the initial analysis of relations between the retrieved parameters was conducted in a statistical manner, detailed understanding of physical reasons behind these relations and their variability will require also substantial modeling efforts in future.

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